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LCA FOR ENERGY SYSTEMS

Comparative life cycle assessment of uses of rice husk for energy purposes

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Abstract
Purpose Recently, the Thai government has been advancing the expanded use of biomass as an alternative source of energy substituting it for the fossil fuels that have been shown to be harmful to the environment. Rice husk, one of the main sources of biomass in Thailand, has already been used as an energy source in many different applications and has been successful in reducing the consumption of fossil fuels. At present (2011), the main use of rice husk in Thailand is as fuel to generate electricity. However, rice husk can potentially be used to produce other forms of energy such as cellulosic ethanol. This paper compares the environmental performance of the current main use of rice husk for energy purposes in the Thai context, i.e., for electricity generation with the prospective use, i.e., for cellulosic ethanol production. The results from this study will identify the more environmentally friendly option for use of rice husk for energy purposes.
Materials and methods To determine the more environmentally friendly rice husk use option, that being the option that showed the greatest reduction of environmental impacts, the environmental impacts of the two selected rice husk use options were compared with the environmental impacts of their conventional energy production processes using the life cycle assessment (LCA). The LCA software package SimaPro 7.1.6 was used to assist in the analysis of the environmental impacts, with the impact assessment method ReCiPe 2008. The system boundary of the study was expanded to take into consideration the effects caused by the consumption of coproducts generated within the two rice husk options. To make the options comparable, the functional units defined for both options were based on processing 1,000 tonnes of rice husk in both rice husk use systems studied.
Results Based on the available data and assumptions made for this study, the results show that the use of rice husk in both electricity and cellulosic ethanol options had a significant effect in reducing the impacts on fossil fuel depletion and climate change, when compared with the conventional processes. However, the use of rice husk in both options caused a slightly higher impact on particulate matter formation than the conventional processes. The option of using rice husk to generate electricity was preferred over the option of using rice husk as a feedstock to produce cellulosic ethanol for all other impact categories analysed, except particulate matter formation, marine eutrophication, photochemical oxidant formation and freshwater ecotoxicity. In addition, it was found that using rice husk to produce cellulosic ethanol caused a considerably greater impact on human toxicity than its conventional product.
Discussion The environmental benefits gained by using rice husk depend on the materials that rice husk is replacing. This means that the reduction of environmental impact depends upon the use of the rice husk.
Conclusions Overall, the option of using rice husk to generate electricity shows benefits over the option of using rice husk to produce cellulosic ethanol for most impact categories analysed. However, the cellulosic ethanol option is better than the electricity option in terms of particulate

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matter formation, marine eutrophication, photochemical oxidant formation and freshwater ecotoxicity.

Recommendations and perspectives In the short run, the option of using rice husk to generate electricity is more environmentally friendly than the option of using rice husk to produce cellulosic ethanol. However, if rice husk is to be used for electricity generation, the ash generated in power plants should be sent out to be used in other industries. It should not be disposed of in landfills as it causes greater impacts than other ash use options. In the time of oil shortages, rice husk should be considered for use as a feedstock to produce cellulosic ethanol for use as a substitute for petrol to help reduce the dependency of oil importation for Thailand. However, the production process of cellulosic ethanol should be improved to help increase efficiency in reducing the environmental impacts in other impact categories.

Keywords Agricultural residue · Biofuel · Comparative LCA · Rice husk · System expansion · Waste management

1 Introduction

Thailand is one of the largest rice producing nations in the world. In 2008, Thailand produced approximately 32 million tonnes of rice (Office of Agricultural Economics 2009). Moreover, there is a trend for Thai rice exports to increase (International Rice Research 2008). This implies that, if the trend continues, there will be an increased quantity of rice husk in the future. Rice husk is a coproduct of rice generated in the rice milling process. This husk accounts for about 23% of the total paddy weight (Prasertsan and Sajjakulnukit 2006). To make use of this large quantity of rice husk, the husk has traditionally been used as an energy source in the rice mills themselves. In the past, unused rice husk was disposed of by open-air burning or dumping which caused significant local pollution. To deal with this problem, substantial research has been conducted to find useful applications for rice husk. The unique features of rice husk and its ash have been found to be useful in several industrial applications. More recently, the Thai government has promoted the use of biomass for energy purposes to substitute for fossil fuel consumption and to reduce the environmental impacts caused by using fossil fuels (Prasertsan and Sajjakulnukit 2006). Therefore, rice husk, which is one of the main sources of biomass in Thailand, has the potential to substitute for fossil fuels.

According to the seventh National Economic and Social Development Plan (1992–1996), the Thai government promoted the privatisation of the energy sector to reduce the investment burden of the government and to raise competition levels in the energy sector. The competition in the sector was expected to increase the efficiency of energy production and to ensure adequate energy at fair prices (Office of the National Economic and Social Development Board 1992). Correspondingly, the Small Power Producer (SPP) scheme was drawn up by the National Energy Policy Council with the purpose of encouraging the private sector to invest in the energy industry (Prasertsan and Sajjakulnukit 2006; Energy Policy and Planning Office 1999; Amornkosit 2007). The SPP is defined as either the power producer using cogeneration technologies or using renewable energy as a fuel (Energy Policy and Planning Office 1999). More recently, the Very Small Power Producer (VSPP) programme was launched with an aim of distributing electricity generation to the rural areas and increasing the public's participation in power generation (Amornkosit 2007; Kalayanamitr 2004). The VSPP is defined as a power producer that has a generation capacity lower than 10 MW and is either a cogenerator or uses renewable energy (Electricity Generating Authority of Thailand (EGAT) 2009). Since rice husk is one of the important renewable energy sources of Thailand, rice husk has been used as fuel in a large number of SPPs and VSPPs (Energy Policy and Planning Office 2009).

Although the current major use of rice husk in Thailand seems to be electricity generation, rice husk can potentially be converted to other forms of energy such as cellulosic ethanol (Saha and Cotta 2008; Saha and Cotta 2007; Saha et al. 2005). Since the Thai energy policy emphasizes the security of energy supply to help reduce dependency of fossil fuel importation, the option of using rice husk to produce cellulosic ethanol also seems to be beneficial to the nation. This paper compares the environmental performance of the main current and potential uses of rice husk for energy purposes, i.e., use in electricity generation and use in cellulosic ethanol production. A comparison of the environmental impacts of these two rice husk uses was presented elsewhere (Prasara-A and Grant 2008). However, the use phase of ethanol has not previously been reported. Also, the results presented in this paper take into account the use of ethanol in vehicles. Moreover, the results presented in this paper are analysed by the recently developed impact method (ReCiPe 2008), while the results presented by Prasara-A and Grant (2008) are analysed by the Eco-indicator 99 method. Importantly, the results of the current study inform the policy makers about energy options.

2 Methodology

2.1 Goal and scope of the study

Goal definition The goal of this research was to compare the environmental performance of uses of rice husk in

electricity generation and in cellulosic ethanol production. To achieve this goal, the life cycle assessment (LCA) was used to assess the environmental impacts associated with the selected rice husk use pathways. In this context, the more environmentally friendly use of rice husk is the use option that shows the reduction of environmental impacts to the larger extent. The environmental impacts of the selected rice husk use pathways are compared with that of the conventional production systems (the production systems of the products that the use of rice husk is to replace). In other words, how the uses of rice husk can help to reduce environmental impacts (in the case that they can) can be seen as how much they can save the consumption of the conventional products. Hence, it is important to define the products where rice husk is used as a substitute in any production process, and assess the environmental impacts associated with the production processes. It is necessary to know the scale of these impacts in order to calculate the relative benefits of their substitution with rice husk.

The choices of conventional products to be investigated are based on the view that the use of rice husk can help to reduce emissions caused by the consumption of fossil fuels. This is to conform to the Thai government policies discussed in the previous section, but not to displace any other existing biomass uses that already assist to reduce the consumption of fossil fuels. Therefore, the conventional systems selected for analysis were fossil fuels and not those that use existing biomass products, which already contribute to the reduction of fossil fuel consumption.

The conventional product chosen for the electricity option was the Thai grid mix production. In considering the cellulosic ethanol option, the conventional product chosen was petrol. Currently, cane molasses is the main feedstock used to make ethanol in Thailand (Nguyen and Gheewala 2008). Nevertheless, in this study, the use of rice husk as a feedstock to generate cellulosic ethanol is seen to complement existing ethanol production in Thailand at times of high oil prices, and ethanol production is currently (2011) in high demand. Therefore, the conventional product chosen for cellulosic ethanol system was petrol (rather than cane molasses-based ethanol).

As this LCA study was conducted to help in making a decision between different rice husk use options, the functional unit for each system was defined based on disposing 1,000 tonnes of rice husk in each rice husk use system. The analysis also took into account the use phase of the products to find out whether there are any differences between the use of the products generated from rice husk use systems and the conventional products. In the case of the electricity system, there is no difference in how the final product (rice husk fuel-based electricity production) is used compared to the conventional product (electricity from the Thai grid). Hence, the functional units for these two systems were defined as the amount of electricity generated by processing 1,000 tonnes of rice husk in the production processes.

Nonetheless, there is a distinction between the use of ethanol and use of petrol. Ethanol is used to blend with petrol to produce gasohol which can be used in existing gasoline-powered engines, while petrol can be used directly in the engines. The percentage of ethanol in gasohol can be varied; however, the E10 (mix of 10% ethanol and 90% of petrol) was used in this study as it can be used in existing vehicles without any engine modification (Goettemoeller and Goettemoeller 2007). Therefore, the functional unit of the cellulosic ethanol system was defined as the use of the amount of ethanol produced from 1,000 tonnes of rice husk (as a feedstock in the ethanol process) in vehicle operation, or how far a vehicle could travel using this amount of fuel. This study then compares vehicle operation using E10 and using petrol based on the same travel distance just described. The definitive functional units for rice husk use systems examined and for their conventional systems are shown in Fig. 1.

The functional units defined in Fig. 1 were used to calculate the environmental impacts associated with rice husk in different rice husk use systems studied. This was done by analysing the environmental impacts caused by the rice husk use systems, including their conventional systems, based on the functional units defined in Fig. 1. From this, to obtain the difference in environmental impact of using 1,000 tonnes of rice husk in each system, the environmental impacts of the conventional system were simply subtracted from that of the rice husk use system (based on the same functional unit). The results from this calculation indicate whether using rice husk in the systems analysed would result in the reduction of the environmental impacts and quantify the changes. Negative results would indicate that the use of rice husk has an effect on the reduction of the environmental impacts.

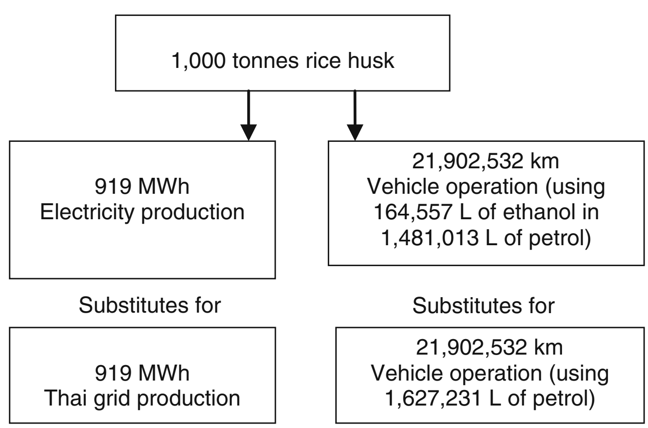

Fig. 1 Definitive functional units for rice husk use systems examined and for their conventional systems

Scope definition A general system boundary of this study is shown in Fig. 2. In this study, rice production is excluded from the system boundary. Therefore, the use of rice husk as a fuel in rice mills is also excluded from the boundary as it is considered as part of rice production. Although the environmental impacts caused by rice production are considered significant, they do not influence how rice husk is utilized. Hence, the system boundary of this study covers the transportation of rice husk from rice mills to the rice husk use sites and the rice husk utilizing processes. In addition, the boundary avoids the production processes of the competing inputs. These inputs refer to the products that rice husk (and the coproduct generated from utilizing rice husk) is used to replace in other applications outside the system boundary. In electricity production, rice husk is assumed to be the sole fuel used in a boiler. The general process of rice husk-fuelled electricity production is described in Chungsangunsit et al. (2004). In cellulosic ethanol production, rice husk is used as a main feedstock. A description of the cellulosic ethanol production process is documented in Aden et al. (2002).

As a comparative LCA study, a system expansion approach is used to take into account the effects of the uses of coproducts in some rice husk use systems examined. For example, some rice husk use systems provide a coproduct which is used in other applications (outside the system boundary) where their conventional systems do not generate a coproduct. Therefore, the use of this coproduct will affect the LCA results when compared with the environmental impacts of the conventional processes. To deal with this coproduct allocation problem, it is suggested that the coproduct allocation is avoided by system expansion (Weidema 2001; Ekvall and Weidema 2004). This is undertaken by avoiding the production processes of the products that rice husk, and the coproduct generated from utilizing rice husk, are used to replace in other applications.

It is conceivable that the changes in the amount of rice husk used in one system may affect another and, consequently, affect the environmental profiles of another system examined; however, this is not the aim of the study. This study aims to determine the rice husk use option, in which the substitution of rice husk for fossil fuels would produce the greater environmental benefit.

In the electricity generation process, rice husk ash is produced from the rice husk combustion process. In this study, the ash was assumed to be either sent to the local ash consumers for use as soil conditioner in the paddy rice fields as a substitute material for clay in clay brick production or as a substitute material for cement in lightweight concrete block production. The option of disposing the ash in a landfill was also taken into account. However, for the uses of the ash in industrial applications, the model did not include the whole production processes of these three options. Only the effects of using rice husk ash in these production processes were taken into account.

2.2 Life cycle inventory analysis

Data sources and modelling Foreground data were obtained from several sources such as interviews with industry personnel, questionnaires, internet, published journal articles and reports. The questionnaires were distributed in August–September 2007 together with interviews with different industry personnel involved with using rice husk in their production. Background data were from LCI databases available in the LCA software that was used in this study (SimaPro version 7.1.6), namely Ecoinvent 2.0

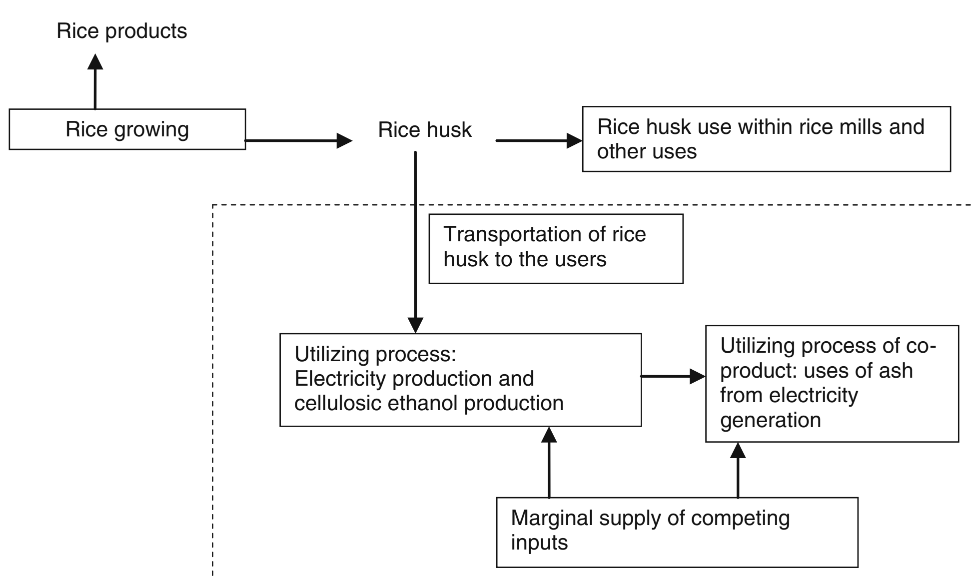

Fig. 2 General system boundary

and Australian Life Cycle Inventory Database, and literature. The Thai LCI database is being developed (Malakul et al. 2005); however, at the time of our study it had not been made available to the public (from personal communication with the organization developing the Thai LCI database in November 2008). However, LCI data for some production processes are available from published reports (Thailand Environment Institute (TEI) 2004; Lohsomboon and Jirajariyavech 2003). LCI modelling was performed in the LCA software SimaPro version 7.1.6. Data sources for each rice husk use system and how its LCI model was created are described below:

1. *Electricity generation system* LCI data for the electricity generation option were mainly collected from one specific rice husk power plant. This specific site was selected because of its state-of-the-art technology (at the time of analysis). This selection was based on the assumption that in the future the use of newer technologies will be greater than that of old technologies, which will affect the environmental impacts of these technologies. Therefore, this study looks at the most modern technology available for each rice husk use system. However, some data were taken from other literature sources to close data gaps as not all data needed could be obtained from this site. Note that different rice husk electricity generation technologies may result in different environmental profiles. However, such an analysis was not the aim of this study, which was to compare the environmental profiles of the selected rice husk use options. To make all options comparable, the most advanced technologies of all rice husk use systems were chosen.

The LCI data for the Thai grid mix were available from a TEI report (Lohsomboon and Jirajariyavech 2003). However, the amounts of the electricity generated from the different fuel types used in this report are not up-to-date (the data of the year 1999–2001). Therefore, the latest data on electricity generation from different fuel types were obtained from the energy statistics of the Energy Policy and Planning Office (EPPO) (2009). The unit process data of electricity production using different fuel types were taken from European and Australian databases (available in SimaPro version 7.1.6). This is to make the LCI model of the Thai grid mix system comparable with that of the rice husk use system. Since this LCA study was conducted for the purpose of comparison between different options, much attention was paid to making the options investigated comparable.

The LCI data for rice husk ash disposal depend on the competing product that the ash is used to substitute for in each ash use option. In lightweight concrete block production, 1 kg of ash is used to substitute for 1 kg of Portland cement, so 1 kg of Portland cement was avoided in the LCI model. In clay brick production, 1 kg of ash is used to substitute for 1 kg of clay. For using the ash as a soil conditioner in rice fields, 500 kg of ash is used to substitute for 24 kg of ammonium sulphate as nitrogen. For disposing of the ash in a landfill, the LCI data were adapted from the unit process 'Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U' in the Ecoinvent 2.0 database in SimaPro version 7.1.6. Note that it was assumed that the transportation distances from the rice husk power plant to all local ash consumers (assumed to be 100 km) as well as the transportation means (assumed to be truck transport) are the same. Since this LCA study compares different rice husk ash disposal options to determine the most preferable option, the transportation process was excluded from the LCI models of all the ash use options as it makes no difference between the options examined.

2. *The cellulosic ethanol system* As the use of rice husk as a feedstock in cellulosic ethanol production had not been introduced to Thailand at the time of analysis, data from other countries were sought. However, there were no LCI data for the production of cellulosic ethanol from rice husk available, instead data for the production process of ethanol were adapted from the production process of cellulosic ethanol production from wood (Jungbluth et al. 2007). As a consequence, ethanol yield and some available inputs were adjusted to rice husk conditions according to Saha et al. (2005). While inputs from TechnoSphere were proportional to dry matter input, emissions of hydrocarbons were proportional to carbon input and all other emissions were proportional to dry matter input according to Jungbluth et al. (2007).

Data about fuel consumption and exhaust emissions released from a passenger car using E10 operated on Thai driving cycle mode were obtained from Tantithumpoosit (2004). The data for test results based on a Toyota 1.6 L/2000 were used in this study. However, the CO_2 emission from using E10 given in by Tantithumpoosit (2004) is not measured as biogenic and fossil CO_2 emissions. The relative proportions of biogenic and fossil CO_2 emissions released from vehicle operation using E10 in Grant et al. (2008) were used to calculate concentrations of biogenic and fossil CO_2 emissions for this study.

Data quality As our analysis used a simplified LCA, our data are not of as high a quality as the data used in a detailed LCA. Where possible, process data were adapted to the Thai conditions. However, there were only a few sets of LCI data of the Thai production processes available. Therefore, most data employed in this study were based on unit process data from Australia and some European

countries as these were available on the LCA software package used in this study (SimaPro version 7.1.6). The data used were also adapted to be as consistent with the goal and scope of the study as possible. As a comparative LCA study, an effort was made to make all LCI models comparable.

Consistency of data As much as possible the same level of detail for unit process data, derived from SimaPro version 7.1.6, was used. For example, LCI data for some processes include infrastructure processes, but some do not. In this study, the infrastructure processes were removed to make all the system models investigated comparable. Moreover, attention was paid to the comparative LCI models. For instance, the LCI model of the cellulosic ethanol system excludes the application processes of the ash generated by burning the residues remaining in the cogeneration process (part of the cellulosic ethanol production) as the data were not available. This model was compared with that of the petrol product which includes waste management processes of the wastes generated in the refinery. To make them comparable, the waste management processes in the model of petrol product were removed.

The biogenic CO_2 was accounted for as neutral for both rice husk use options studied. According to IPCC (2006), CO_2 released by burning rice husk is counted as neutral because it is assumed that the CO_2 will be reabsorbed during the next season of the rice growing phase. This credit was given to both rice husk use systems to make them comparable as suggested in Christensen et al. (2008). The summary of LCI data used in this study can be found in Prasara-A (2010). Note that data about fuel consumption and exhaust emissions from E10 use can be found in Tantithumpoosit (2004).

2.3 Life cycle impact assessment

The impact assessment method used in this study was ReCiPe 2008 version 1.01, using midpoint indicators, hierarchist (H) and world normalization factors. It was used in the manner set up in SimaPro 7.1.6. The ReCiPe 2008 method was developed by Goedkoop et al. (2009), based on two main approaches: the baseline method for impact characterisation in the handbook on life cycle assessment (Guinee 2002) and the Eco-indicator 99 impact assessment method (Goedkoop and Spriensma 2001). The ReCiPe 2008 method offers results at both midpoint and endpoint levels (Goedkoop et al. 2009). However, this study uses the midpoint results because the results from midpoint level are relatively robust as recommended in the handbook on life cycle assessment (Guinee 2002). In addition, Goedkoop et al. (2009) noted that the uncertainty of the endpoint results analysed by the ReCiPe 2008 method were relatively high compared with that of the midpoint results. This is because the endpoint results are calculated based on their own models. While for the midpoint results, they are based on the internationally accepted models. Hence, the midpoint results analysed by the ReCiPe 2008 method were used. H perspective was chosen as its characteristics are considered appropriate for the aim of this study. According to Goedkoop et al. (2000), the H version supposes that proper policy can help manage the problems. The H version therefore seems to be appropriate for this study which aims to generate recommendations about the rice husk disposal strategies for the policy makers.

2.4 Process contribution analysis

The process contribution analysis was performed to help determine the unit processes that play significant roles in the LCA results. Then the data of the processes and systems, which play significant roles in the overall LCA results, were checked for their quality.

3 Results

3.1 Rice husk based electricity generation and the coproduct uses

In the electricity system, the use of the coproduct (ash) generated in the electricity production process was taken into account. The environmental impacts of selected rice husk ash uses, namely soil conditioner, brick production, lightweight concrete block production and landfill, were assessed and compared to identify the most environmentally favourable rice husk ash application option (among the ones investigated). Then, the best rice husk ash use option from this result was incorporated into the electricity system model for comparison with the cellulosic ethanol system in Section 3.2. The normalized impacts of the production of 919 MW h of electricity produced from rice husk-based electricity generation (which refers to processing 1,000 tonnes of rice husk in the production process) with different ash disposal options are presented in Fig. 3.

Based on how the LCI models were set up for the purpose of assessing the impacts reduced by using rice husk in different rice husk use systems investigated (discussed in Section 2.1), the negative results indicate the benefits of using rice husk (or coproduct) in that use option. In other words, the negative results imply that the process using rice husk (or coproduct) causes less impact than its conventional process.

In Fig. 3, it is clear that the worst option for rice husk ash disposal is landfill. This option causes the highest

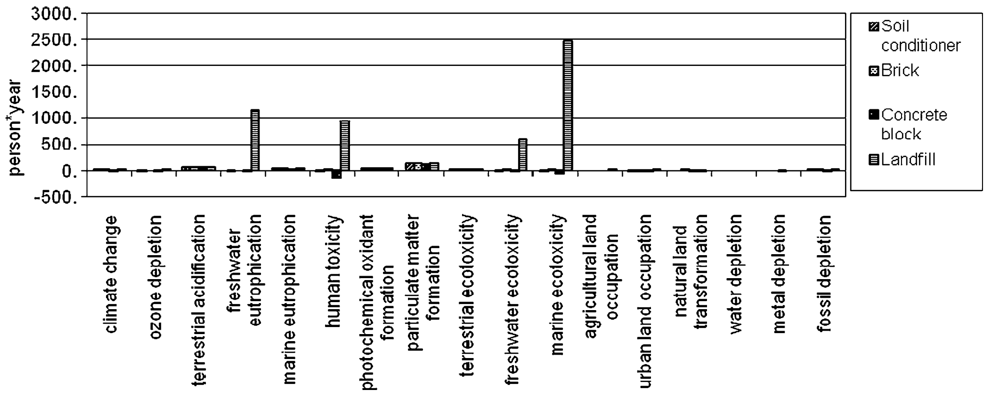

Fig. 3 Normalized impacts of 919 MWh rice husk-based electricity production with different ash use options (analysed by ReCiPe Midpoint (H) V1.01/World ReCiPe H/normalization)

impacts on freshwater eutrophication, human toxicity, and freshwater and marine ecotoxicity, than other ash use options examined. The most environmentally friendly option is the use of the ash in lightweight concrete block production. This option causes less impact on climate change, terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, freshwater ecotoxicity, marine ecotoxicity and fossil fuel depletion. All other ash uses have relatively similar benefits.

3.2 Comparison across different rice husk use options

Table 1 shows the characterized impacts that are reduced by processing 1,000 tonnes of rice husk in the systems examined. The characterized result units differ across impact categories, so it is difficult to compare the results across the different impact categories. Therefore, the normalized results, which are expressed in the same unit for all impact categories, i.e., person × year, were used for a comparison of the environmental impacts. Figure 4 shows a comparison of the normalized results of the two rice husk use systems investigated. Note that for the electricity generation system, the option of sending rice husk ash to use in the lightweight concrete block production is taken into account as it is the most preferable rice husk ash disposal option (results are shown in Section 3.1).

Figure 4 shows that, when compared with conventional products, using rice husk in both electricity and cellulosic ethanol options can help to reduce impacts on fossil fuel depletion and climate change. This is indicated by the significant negative results shown for these impact categories across all categories analysed. The electricity option can help to produce greater impact reductions than the cellulosic ethanol option for all other impact categories analysed, except particulate matter formation, marine eutrophication, photochemical oxidant formation and freshwater ecotoxicity. Also, it should be noted that the use of

Table 1 Characterized impacts reduced by processing 1,000 tonnes of rice husk in electricity and ethanol systems (analysed by ReCiPe Midpoint (H) V1.01/World ReCiPe H/characterization)

Impact category	Unit	Electricity option	Ethanol option
Climate change	kg CO_2 eq	−9.53E+05	−2.43E+05
Ozone depletion	kg CFC-11 eq	−1.85E-04	−7.70E−02
Terrestrial acidification	kg SO_2eq	−5.83E+02	1.04E+03
Freshwater eutrophication	kg Peq	−4.28E−03	−1.07E−01
Marine eutrophication	kg Neq	8.03E+00	−1.25E+02
Human toxicity	kg 1,4-DCB eq	−1.61E+04	2.29E+04
Photochemical oxidant formation	kg NMVOC eq	−3.16E+02	−1.25E+03
Particulate matter formation	kg PM10 eq	1.10E+03	1.04E+02
Terrestrial ecotoxicity	kg 1,4-DCB eq	−3.77E−03	1.14E+01
Freshwater ecotoxicity	kg 1,4-DCB eq	−1.02E+02	−1.60E+02
Marine ecotoxicity	kg 1,4-DCB eq	−1.10E+02	5.37E+01
Agricultural land occupation	m^2 × year	−3.37E+00	2.85E+01
Urban land occupation	m^2 × year	−2.47E+02	−7.02E+00
Natural land transformation	m^2 × year	−2.33E+01	−2.29E−02
Water depletion	m^3	−1.98E+03	−2.31E+04
Metal depletion	kg Fe eq	−5.13E+02	−8.84E+01
Fossil fuel depletion	kg oil eq	−3.05E+05	−1.29E+05

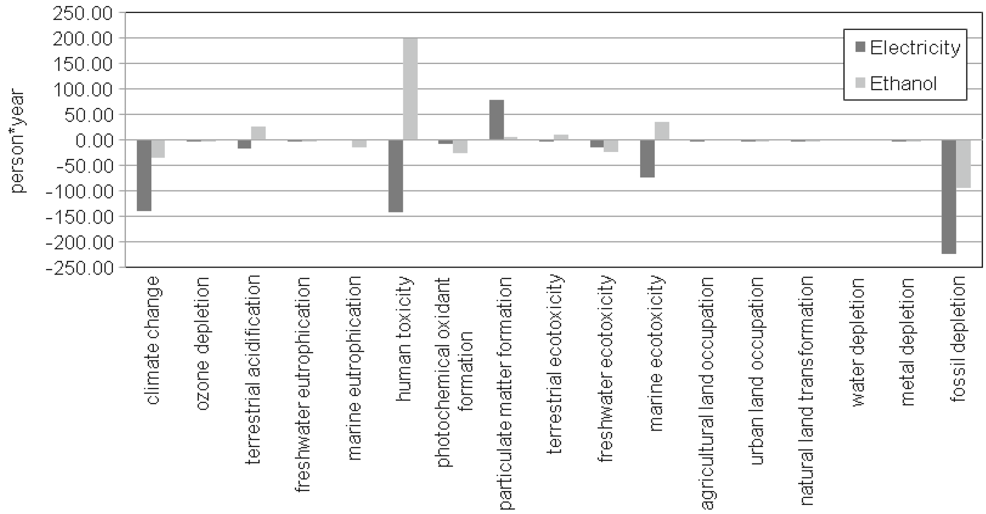

Fig. 4 Normalized impacts reduced by processing 1,000 tonnes of rice husk in electricity and ethanol systems (analysed by ReCiPe Midpoint (H) V1.01/World ReCiPe H/normalization)

cellulosic ethanol produced from rice husk causes considerably greater impact on human toxicity than its conventional product (petrol).

4 Discussion and conclusions

Considering rice husk ash (generated in a rice husk-based power plant), its use in lightweight concrete block production shows the largest benefits over other ash uses examined. This results from the higher environmental credit given to this ash disposal option by substituting rice husk ash for Portland cement in the concrete block production process. This implies that the environmental impacts associated with processing the amount of Portland cement replaced by rice husk ash is higher than that of other conventional products, such as chemical fertilizer or clay. All other ash use options have fairly similar benefits except landfill which causes a lot higher impact on freshwater eutrophication, human toxicity, freshwater and marine ecotoxicity than other ash use options. These impacts result from the emissions in the landfill leachate, which is distributed to groundwater and other water sources.

The reduction of impacts by using rice husk ash in different applications also depends on the efficiency of using the ash to substitute for different conventional products. For example, 1 kg of the ash can be used to replace 1 kg of Portland cement and clay, in lightweight concrete block production and clay brick production. While for using the ash as a soil conditioner in paddy rice field, the ash cannot totally replace chemical fertilizer as the rice plants need both rice husk ash and chemical fertilizer for higher yields (Songmuang 2000). However, the substitution rate of rice husk ash for the conventional products in different ash use options needs to be considered when making decisions about husk uses.

Generation of electricity using rice husk shows benefits over its conventional production system (the Thai grid production) in all impact categories examined, except particulate matter formation. Chungsangunsit et al. (2004) found similar benefits of rice husk-based electricity generation over the Thai grid production. However, the study of Chungsangunsit et al. (2004) excludes the utilization of rice husk ash produced in the combustion process, compared with our study which includes the use of rice husk ash. Moreover, the impacts in toxicity categories are not analysed in Chungsangunsit et al. (2004).

The use of rice husk for cellulosic ethanol production is obviously better than its conventional system (petrol) for climate change and fossil fuel depletion. A study of González-García et al. (2009) also found that the use of cellulosic ethanol to replace petrol can help to reduce the global warming and fossil fuel depletion. However, the impacts in toxicity categories are not analysed in González-García et al. (2009). In addition, results from the study of Spatari et al. (2005) show that the use of cellulosic ethanol can help to reduce greenhouse gases in both near term and midterm. This supports the benefit of the use of cellulosic ethanol over the use of petrol in terms of climate change. However, the impacts of the use of cellulosic ethanol in other impact categories should also be considered. This study found that the cellulosic ethanol option also shows benefits over its conventional system in terms of marine eutrophication, photochemical oxidant formation and freshwater ecotoxicity.

From our analysis, we found that the cellulosic ethanol option causes notably higher impacts on human toxicity, terrestrial acidification, terrestrial and marine ecotoxicity

than its conventional system while the electricity option can help to reduce impacts on these categories. For the cellulosic ethanol system, the main substances contributing to human toxicity are phosphorus, manganese, vanadium, lead, zinc, mercury and cadmium. The main contributing substances for terrestrial and marine ecotoxicity are vanadium, copper, zinc, phosphorus, nickel, manganese, bromine and chlorine. These emissions are mainly from the production process of the cellulosic ethanol itself. This may result from the process of burning solid residues left from ethanol distilleries (to produce heat and electricity for use in the ethanol plant and then sell the surplus amount to the grid). The main substances distributing to terrestrial acidification are SO_2, NO_x and NH_3. These emissions are mainly released from the production of sulphuric acid which is one of the main raw materials used in the cellulosic ethanol production. This implies that if the production process of rice husk-based cellulosic ethanol can be improved, this will increase an efficiency of the ethanol option in reducing impacts on human toxicity, terrestrial acidification, terrestrial and marine ecotoxicity.

Particulate matter formation seems to be a problem when using rice husk in both electricity and cellulosic ethanol systems. In the cellulosic ethanol system, the main substances distributing to particulate matter formation are SO_2, NO_x, NH_3 and PM. These emissions are mainly released from the production of sulphuric acid (where the fossil fuels are burned in the distillery process). Sulphuric acid is one of the main raw materials used in the production of cellulosic ethanol, but it is not used in petrol production. Note that producing cellulosic ethanol from rice husk requires more sulphuric acid compared to other lignocellulosic material such as wood (Jungbluth et al. 2007; Saha et al. 2005). In the electricity generation system, the main substances causing particulate matter formation are PM, SO_2 and NO_x. These emissions are released during the combustion of rice husk in a boiler. It is also reported by Chungsangunsit et al. (2004) that rice husk-based electricity generation causes a considerably higher PM emission than the Thai grid production. Therefore, when using rice husk for either electricity or cellulosic ethanol production, attempts need to be made to lower these emissions in order to help reduce particulate matter formation.

Overall, the electricity option is preferred over the cellulosic ethanol option in most impact categories, except for particulate matter formation, marine eutrophication, photochemical oxidant formation and freshwater ecotoxicity. This is because the cellulosic ethanol option has lower efficiency in substituting rice husk for fossil fuel than the electricity option. In electricity generation, rice husk is used directly as a fuel to produce electricity. Whereas, in the cellulosic ethanol option, rice husk is used as a feedstock to produce ethanol, after which ethanol is used to make E10. Moreover, ethanol has about two thirds of the energy content of petrol (Grant et al. 2008), hence, a larger volume of E10 is required to replace petrol to operate vehicle on the same distance.

5 Recommendations and perspectives

At the time of any oil shortage in Thailand, it is suggested that rice husk should be considered for use in cellulosic ethanol production to help reduce oil imports. However, the cellulosic ethanol option has a low efficiency in substituting for fossil fuel. Hence, it has a low efficiency in reducing the environmental impacts. It is expected that an improvement of the cellulosic ethanol production process would help increase the efficiency of the ethanol option and improve the capacity to reduce environmental impacts.

If rice husk is to be used for electricity generation, the ash generated in power plants should be used in other industries. It should not be disposed of in landfills as there is no environmental credit gained this way. Moreover, disposal of ash in landfills causes a lot greater impact on freshwater eutrophication, human toxicity, freshwater and marine ecotoxicity than other ash use options.

However, the LCA results presented in this paper only provide supporting information from the environmental point of view. Before making decisions about energy options, it would be necessary to take into account other information, such as that relating to economic and social implications.

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